NASA CR-
147710

Final Report
October 10, 1974

Contract NASA 9-13545

Submitted to

National Aeronautics and Space Administration
Lyndon B. Johnson Spacecraft Center
Houston, Texas 77058

Operation of Agricultural Test Fields for Study of Stressed Crops by Remote Sensing

Submitted by

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(NASA-CR-147710) OPERATION OF AGRICULTURAL TEST FIELDS FOR STUDY OF STRESSED CROPS BY REMOTE SENSING Final Report, 1 Jun. 1973 - 30 Sep. 1974 (Texas A&M Univ.) 62 p HC $4.50 CSCL 02C G3/43

N76-23672

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The following summarizes the progress of NASA Contract 9-13545 which was activated June 1, 1973 and ended September 30, 1974. Tasks covered and completed are 1.1 Collection of ground truth on winter wheat, 1.2 Virus stress study and 1.3 Moisture stress study.

1.1 Collection of ground truth on winter wheat

A ground truth area of hard red winter wheat was established west of Hale Center, Texas in February, 1973. Maps showing the location of winter wheat fields in excess of 40 acres in size within a 10 mile radius were supplied NASA. This test area was in Hale county north of the Texas Agricultural Research and Extension Center at Lubbock, Texas. Satellite data was collected for this test site (ERTS-1).

The only imagery that was not obstructed by cloud cover was collected April 18, 1973. The wheat was harvested in May and June. No comparative assessment could be made on the one photograph available.

A test site for the study of winter wheat development and collection of ERTS data was established in September of 1973. The test site is a ten (10) mile square area (100 sq. miles) located 12.5 miles west of Amarillo, Texas on Interstate Hwy. 40, in Randall and Potter counties. The center of the area is the Southwestern Great Plains Research Center at Bushland, Texas.

Within the test area all wheat fields were identified by ground truth and designated irrigated or dryland. The fields in the test area other than wheat were identified as to pasture or the crop that was grown

in the summer and fall of 1973 i.e. sorghum, sugarbeets, soybeans. Soil maps of the test area in Potter county with the fields indicated and the crop designated were supplied to Mr. Tom McPherson NASA.

The wheat in the test site area was seeded in September and October 1973. October survey for Wheat Streak Mosaic Virus revealed no mosaic present. However, heavy infestations of aphids (greenbug) *Schizaphis graminum* were present.

In November, no Wheat Streak Mosaic was observed but greenbugs were heavily populating the wheat and causing some damage. In addition the dryland wheat was showing effects of drought.

Environmental data was collected at the Bushland test site from October 1, 1973 to June 30, 1974. Data is attached for October through June that includes i.e. Maximum Temperature, Minimum Temperature, Wind Movement, Evaporation, Precipitation, Integrated Solar Radiation, Net Solar Radiation, Relative Humidity, Soil Temperature, and Soil Moisture (Appendix A)

I met with Mr. Tom McPherson and Mr. Edward Krauss of NASA at the test site on January 23, 24 and 25. I supplied maps and ground truth data on the fields in the test site area in addition to radiation data collected each date of the ERTS pass. At that time we selected a smaller test site within the area for collection of spectral reflectance data from a helicopter platform. The smaller test area includes wheat fields and one field of rye.

The surveys for Wheat Streak Mosaic revealed no mosaic present during December, January and February. However, symptoms are mask during cold weather.

Many of the dryland wheat fields in the area were abandoned by March 15, 1974 due to dry weather. Precipitation in the area from October 1 to January 31 totaled only 1.57 inches and 9.35 inches for the growing season.

The ground truth data was completed for the bushland test site in August 1974. Data for each wheat field in the test site area (thirty in total) included: Variety, Fertilization, Irrigation, Grazing scheme, Insect, Disease, Hail, Weed conditions and yield. The data is attached in Appendix B.

1.2 Virus stress study

The land was prepared and grain sorghum planted for the virus test plots on April 13, 1973 on the Brazos River Bottom Farm of the Texas Agricultural Experiment Station, College Station, Texas. When the sorghum plants reached the three leaf stage of growth 50' x 40' plots were established.

Five treatments of 0, 25, 50, 75 and 100 percent virus inoculations were replicated three times making a total of 15 plots. In addition another eight plots were established with two treatment i.e. 0 and 100% virus inoculated, replicated four times. Inoculations with Maize Dwarf

Mosaic Virus were made with a tractor mounted airbrush on May 22, and May 24, 1973. Virus symptoms appeared on June 4. The plots were cultivated for weed control, irrigated and sprayed for insect control as needed. Results of soil moisture, plant density and moisture content, and soil temperature monitored on these plots are attached.

An additional study on the plots planted for the virus stress study was conducted in July and August, 1973. Soil moisture plant density and moisture content and soil temperature were established for a microwave study. Microwave data was collected on intact green plants i.e. canopy, July 19. This canopy was desiccated with a chemical on August 15, to provide a canopy of dried foliage. The desiccant was about 80% effective in killing the leaves but most stems remained green. Microwave data was again collected on the desiccated plants August 28. All plant material was removed from these plots and microwave data was collected on the bare soil August 30. The field studies were complete and terminated on that date. Soil moisture, plant density, plant moisture content and soil temperature are attached in Appendix C.

1.3 Moisture stress study

An array of twelve lysimeters equipped with a system for controlling soil moisture was provided. Twelve lysimeter plots were prepared and planted with grain sorghum on April 14, 1973. The plots were irrigated at intervals to allow moisture stress. Adjacent to the lysimeter 40 foot

plots were planted to grain sorghum and inoculated with Maize Dwarf Mosaic Virus. The lysimeter areas were hand weeded, irrigated and sprayed for insect control during the growing season. Systems monitored for these plots included: growth of the sorghum, disease development, water content of the soil, humidity, temperature, wind and radiation. The microwave scan on the lysimeter area was made on July 20, 1973. A summary of the evaptranspiration and water use efficiency data of the grain sorghum under study is included in Appendix D.

Appendix A

Environmental Data

Bushland Test Site

October 1, 1973 to June 30, 1974

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1973

October	Maximum Temp* °F	Minimum Temp* °F	Wind Movement* Miles	2' Evaporation Pa Inches	Precipitation* Inches	Integrated Solar Radiation, cal/cm	Net Radiatio cal/cm^2 Pos.	cal/cm^2 Neg.	Relative Humidi.. at Max Temp 1/	Soil Temp 2/ °F 2"	6"	Soil Moisture 3/ inches total H_2O 0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1	78	44	91.0	0.15		498	238	82		62	64						
2	90	48	131.3	0.16		490	232	78	8	66	67						
3	93	49	106.7	0.27		422	198	64	7	65	67						
4	91	48	204.6	0.23		217	127	15	9	63	66						
5	60	48	90.7	0.20		59	4	11	36	63	64						
6	55	45	128.5	0.07	1.05	454	267	54	44	58	59						
7	80	50	138.5	0.10		472	262	72	30	60	62						
8	84	52	130.4	0.19		444	250	35	16	60	61						
9	85	55	217.3	0.17		459	241	71	20	65	65						
10	82	49	126.4	0.24	T 4/	109	72	72	8	60	62						
11	52	33	177.1	0.20	T	470	236	91	72	54	55						
12	65	34	114.8	0.08		440	222	82	24	55	57						
13	77	40	80.8	0.21		448	258	82	10	54	56						
14	71	39	65.5	0.07		446	229	82	37	56	58						
15	72	39	67.0	0.14		430	218	72	20	57	59						
16	79	44	71.4	0.08		251	140	74	16	57	59						

17	65	41	77.1	0.10	421	230	77	38	55	58						
18	77	41	94.5	0.22	442	210	81	25	56	58						
19	82	43	92.1	0.15	426	199	92	14	56	59						
20	82	43	77.4	0.10	412	195	75	15	57	60						
21	80	44	90.7	0.18	419	190	75	16	58	60						
22	85	44	84.8	0.20	422	190	97	9	58	60						
23	87	44	101.2	0.08	421	190	106	10	57	60						
24	83	42	201.3	0.32	420	188	106	12	57	60						
25	76	38	70.9	0.18	402	182	95	19	56	59						
26	74	38	71.6	0.14	393	186	64	32	57	59						
27	65	38	175.0	0.17	380	164	69	31	56	58						
28	63	36	39.2	0.07	396	176	82	26	53	55						
29	65	35	65.9	0.18	390	184	88	23	53	55						
30	79	43	195.9	0.21	141	80	67	15	55	57						
31	53	35	105.4	0.08	390	176	85	66	50	52	3.22	4.05	3.97	3.71	3.55	3.32

*Readings made at 0800 local time and are for previous 24-hr period.
1/Relative humidity taken from hygrothermograph (on day occurred).
2/Soil temp. taken under short grass sod at 0800 local time.
3/Soil moisture measurements made on area seeded to dryland wheat using a neutron meter.
Top foot measurements have been corrected to compensate for neutrons lost to atmosphere.
4/Trace, less than 0.01.

1973 November	Maximum Temp* °F	Minimum Temp* °F	Wind Movement* miles	2' Evaporation inches	Precipitation* inches	Integrated Sola Radiation, cal/	Net Radiation cal/cm^2 Pos.	Neg.	Relative Humidi at Max Temp	Soil Temp[2] °F 2"	6"	Soil Moisture[3] inches total $H_2$0 0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1	70	35	101.7	0.21		384	175	93	21	51	53						
2	82	31	191.9	0.17		353	178	86	9	52	54						
3	51	30	86.9	0.16		302	152	64	46	50	52						
4	63	35	127.5	0.10		292	155	74	34	52	53						
5	56	31	140.3	0.11	T[4]	71	28	6	48	50	51						
6	40	31	154.1	0.10		358	150	61	82	49	50						
7	77	33	104.3	0.07		367	137	82	10	50	52						
8	77	40	66.9	0.07	T	251	115	28	10	54	55						
9	68	40	104.2	0.12	0.02	52	7	11	28	53	55						
10	45	38	109.1	0	T	274	148	50	100	50	52						
11	63	32	149.5	0.08		349	140	85	38	48	52						
12	72	33	91.3	0.12		347	152	95	NA[6]	51	53						
13	83	41	161.3	0.12		291	116	79	7	52	53						
14	82	46	85.1	0.08		212	88	83	10	53	55						
15	76	30	123.1	0.21		353	135	92	15	49	52						
16	62	29	65.2	0.14		340	146	91	15	46	50						

November, 197 tinued

17	69	34	182.8	0.14		307	126	94	20	48	51						
18	75	38	131.2	0.20		313	113	89	11	48	51						
19	75	37	45.2	0.14		235	92	68	12	49	51						
20	71	24	214.2	F 5/	0.03	207	82	64	32	45	50						
21	35	23	138.1	F	T	323	150	90	54	42	45						
22	65	24	147.2	F		314	124	83	12	41	45						
23	66	28	50.6	0.40	T	176	58	38	12	46	49						
24	62	32	54.4	0.05		238	99	86	18	44	46						
25	61	29	65.4	0.09		167	84	82	14	44	46						
26	55	32	160.3	0.13		304	132	88	22	44	47						
27	57	24	148.2	F	T	280	150	76	17	41	47						
28	45	16	131.7	F	T	315	130	89	27	37	41						
29	61	26	58.2	F		315	130	89	7	40	43	2.88	3.75	3.84	3.68	3.53	3.31
30	72	27	111.5	F		324	120	82	15	41	44						

Last Sampling Date - 10/31/73

*Readings made at 0800 local time and are for previous 24-hr period.
1/Relative humidity taken from hygrothermograph (on day occurred).
2/Soil temp. taken under short grass sod at 0800 local time.
3/Soil moisture measurements made on area seeded to dryland wheat using a neutron meter. Top foot measurements have been corrected to compensate for neutrons lost to atmosphere.
4/Trace, less than 0.01
5/F-frozen.
6/NA-not available.

Bushland, Texas

1973

December	Maximum Temp* °F	Minimum Temp* °F	Wind Movement* miles	2' Evaporation Pan* inches	Precipitation* inches	Integrated Solar Radiation, cal/cm 2	Radiation cal/cm^2 Pos.	Radiation cal/cm^2 Neg.	Relative Humid. at Max Temp 1/	Soil Temp 2/ °F 2"	Soil Temp 2/ °F 6"	Soil Moisture 3/ inches total H_2O 0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1	80	27	70.3	0.56		3.13	120	76	9	40	45						
2	75	29	214.0	0.14		296	128	87	17	44	46						
3	74	32	226.1	F 5/	0.02	77	15	41	22	46	48						
4	33	23	241.4	F	0.15	313	43	83	100	42	43						
5	38	22	150.4	F		319	125	94	80	39	41						
6	42	18	48.2	F		300	133	87	57	37	39						
7	46	20	104.6	F		302	140	78	42	36	38						
8	55	20	65.0	F		272	140	75	33	35	37						
9	54	27	123.4	F		293	135	80	43	36	38						
10	44	21	53.0	F		290	121	76	34	35	37						
11	59	23	91.3	F		282	125	74	32	36	37						
12	63	32	93.5	1.36		283	114	99	26	48	50						
13	66	27	132.9	F		258	119	71	19	37	39						
14	55	29	100.4	0.22		263	128	52	39	38	40						
15	52	24	100.3	F		286	112	68	50	38	40						
16	50	19	73.8	F		286	116	66	25	36	38						

17	59	22	83.6	F		237	103	57	23	36	38
18	67	29	29.9	0.29		282	121	45	26	37	39
19	65	11	372.8	F	T4/	274	149	56	24	35	37
20	26	3	194.9	F	T	306	123	85	66	33	35
21	46	5	106.0	F		291	123	49	26	33	35
22	63	19	59.5	F		304	102	70	21	33	35
23	73	25	66.4	F		278	115	37	12	35	36
24	47	23	153.6	F	0.01	124	55	30	47	35	37
25	30	12	185.3	F	0.02	265	96	66	100	34	36
26	48	13	165.2	F		292	154	69	29	34	35
27	39	11	123.8	F		255	116	77	51	33	35
28	56	17	247.2	F		195	88	56	18	34	35
29	63	21	130.9	F		298	131	61	34	35	37
30	55	22	168.2	F		164	107	33	33	37	38
31	34	5	186.2	F		146	78	13	88	34	36

*Readings made at 0800 local time and are for previous 24-hr period.
1/Relative humidity taken from hygrothermograph (on day occurred).
2/Soil temp. taken under short grass sod at 0800 local time.
3/Soil moisture measurements made on area seeded to dryland wheat using a neutron meter.
Top foot measurements have been corrected to compensate for neutrons lost to atmosphere.
4/Trace, less than 0.01.
5/F-frozen.

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1974 January	Maximum Temp* °F	Minimum Temp* °F	Wind Movement* miles	2' Evaporation P. inches	Precipitation* inches	Integrated Solar Radiation, cal/c	Radiation cal/cm² Pos.	Neg.	Relative Humidi at Max Temp 1/	Soil Temp 2/ °F 2"	6"	Soil Moisture 3/ inches total H_2O 0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1	20	5	103.7	F 5/	0.05	207	43	11	81	32	34						
2	13	2	165.4	F	T 4/	[illegible]1	57	4	100	32	34						
3	14	7	191.9	F	T	293	30	12	88	32	33						
4	15	0	99.1	F		293	101	37	49	31	33						
5	47	4	102.2	F		133	85	48	47	31	32						
6	48	4	112.6	F		261	119	67	37	30	33						
7	50	6	92.3	F		60	43	4	49	30	33						
8	49	29	57.2	F		257	148	22	31	31	33						
9	66	8	226.4	F	0.03	81	24	6	100	31	33						
10	34	10	144.1	F	0.12	80	65	16	100	31	33						
11	27	14	51.6	F	T	62	64	28	100	31	32						
12	24	17	26.9	F	T	113	94	48	100	31	32						
13	34	21	105.9	F		299	165	48	28	31	32						
14	58	30	88.1	F		321	148	72	26	31	32						
15	60	25	77.4	F		331	140	75	18	32	34	2.85	3.59	3.69	3.59	3.44	3.26
16	68	25	49.5	F		325	149	59	15	34	35						

Last Sampling Date - 11/29/73

17	73	25	53.3	F		325	149	59	23	36	37
18	71	35	91.0	F		83	48	19	74	40	40
19	45	23	227.2	F		287	131	58	38	36	37
20	59	24	90.5	F		321	143	68	28	37	39
21	63	31	92.5	F		255	142	44	29	40	40
22	76	31	196.4	F		183	99	36	54	41	41
23	39	15	94.7	F		291	140	72	29	35	37
24	45	14	19.9	F		321	136	71	31	34	35
25	49	18	25.9	F		333	168	72	39	34	36
26	55	18	236.9	F		347	150	91	23	35	37
27	71	25	111.3	F		115	72	80	100	36	38
28	39	17	131.2	F	0.07	363	161	86	32	35	36
29	50	18	63.8	F		361	170	81	20	35	37
30	54	20	104.0	F		306	141	99	13	35	36
31	66	26	152.8	F		371	153	91	17	36	37

*Readings made at 0800 local time and are for previous 24-hr period.
1/Relative humidity taken from hygrothermograph (on day occurred).
2/Soil Temp. taken under short grass sod at 0800 local time.
3/Soil moisture measurements made on area seeded to dryland wheat using a neutron meter.
Top foot measurements have been corrected to compensate for neutrons lost to atmosphere.
4/Trace, less than 0.01.
5/F-frozen.

Bushland, Texas

February 1974

Day	Maximum Temp. °F	Minimum Temp. °F	Wind Movement Miles	2' Evaporation Pan Inches	Precipitation Inches	Integrated Solar Radiation, cal/cm 2	Net Radiation cal/cm2 Pos.	Net Radiation cal/cm2 Neg.	Relative Humidity at Max. Temp.	Soil Temperature °F 2"	Soil Temperature °F 6"
1	67	27	135.9	Not Measured		356	146	105	17	38	39
2	63	28	74.6			319	154	79	28	38	40
3	52	19	83.6			363	158	72	35	36	38
4	57	20	61.5			379	172	85	26	36	37
5	66	19	218.1			370	155	105	15	37	38
6	67	16	267.4			332	187	55	14	38	40
7	31	16	159.1		0.05	332	148	38	53	35	36
8	35	13	164.3			398	184	87	33	34	35
9	42	16	122.6			392	182	82	17	33	35
10	55	24	94.6			401	193	78	24	35	37
11	55	19	68.1			409	186	82	32	36	37
12	69	20	149.5			412	173	90	11	37	39
13	69	35	95.4			373	151	64	12	41	41
14	67	31	80.4			167	71	33	22	41	42
15	52	32	92.1		0.65	403	226	46	61	41	41
16	60	29	53.1			412	216	82	33	40	42
17	61	29	111.7			338	177	62	33	41	42
18	70	32	133.1			268	145	76	16	42	42
19	47	22	177.0			441	208	75	57	37	39
20	64	23	95.8			315	129	74	19	40	42
21	64	31	319.8		0.01	460	230	92	25	40	40
22	45	19	241.0			460	230	92	19	36	38
23	59	21	184.8			437	238	90	15	37	40
24	49	15	211.7			451	240	85	22	36	39
25	44	12	97.8			458	220	78	25	35	37
26	58	11	98.7			463	256	91	18	36	38
27	68	24	208.0			395	184	77	13	39	40
28	74	26	86.6			418	214	72	14	40	42

Bushland,
Texas

February
1974

(Contd.)

	Soil Moisture, inches total H_2O					
	0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28	2.87	3.54	3.56	3.53	3.45	3.27

To find available soil water, subtract the following amounts from total water amounts.

Unavailable Soil Water

0-1'	-	2.34
1-2'	-	2.44
2-3'	-	2.56
3-4'	-	2.52
4-5'	-	2.68
5-6'	-	2.79

Mar. 1974	Maximum Temp.	Minimum Temp.	Wind Movement Miles	2' Evaporatic… Inches	Precipitation Inches	Integrated So… Radiation, ca…	Net Radiation cal/cm^2 Pos.	Neg.	Relative Humi… at Max. Tem…	Soil Temperat… °F 2"	6"
1	67	31	71.6			431	208	54	26	44	44
2	79	37	91.1			354	181	65	21	45	46
3	80	44	229.8			358	182	68	25	48	48
4	77	42	203.6			475	228	90	25	48	48
5	61	24	95.3			507	234	94	30	44	46
6	72	26	151.8			499	262	87	21	46	47
7	78	36	200.3	pans cleaned & filled		253	116	48	17	47	48
8	73	39	139.3	0.08	0.02	408	230	99	46	49	50
9	74	47	161.5	0.13	0.03	93	60	37	39	54	52
10	65	35	282.9	overflow	1.67	81	90	58	100	42	45
11	46	34	145.8	from wind & rain	0.01	541	275	88	100	41	43
12	67	33	115.0	0.12		497	292	80	21	44	46
13	63	34	140.5	0.14		400	272	65	34	46	47
14	68	38	205.9	0.09		478	292	62	47	46	47
15	57	39	112.7	0.09		310	199	75	54	47	48
16	52	30	148.6	0.08		522	303	64	51	42	45
17	68	30	171.0	0.13		486	260	72	29	46	47
18	82	39	80.7	0.22		528	282	68	12	50	50
19	80	39	159.0	0.24		351	197	31	16	52	52
20	62	36	150.3	0.13		63	42	35	47	49	50
21	43	22	212.5	Frozen	TR	525	300	34	100	40	42
22	57	26	185.8	0.40		550	289	80	30	43	44
23	68	19	211.8	Frozen		186	131	8	10	43	45
24	25	15	140.5	Frozen		495	309	47	76	38	40
25	50	18	250.4	Frozen		559	292	69	34	39	41
26	69	21	133.6	0.64		581	309	73	18	45	46
27	78	33	171.8	0.22		555	300	61	12	50	50
28	80	42	145.54	0.26		574	278	64	14	52	52
29	77	44	177.7	0.33		585	302	71	14	53	53
30	73	39	122.4	0.25		562	282	73	22	52	53
31	86	41	149.8	0.31		585	318	89	17	56	55

Bushland, Texas (Contd.)

March
1974

	Soil Moisture, inches total H_2O					
	0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14	3.86	3.57	3.45	3.47	3.41	3.23
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25	3.34	3.53	3.43	3.43	3.40	3.23
26						
27						
28						
29						
30						
31						

Texas

April
1974

	Maximum Temp.	Minimum Temp.	Wind Movement Miles	2' Evaporatic Inches	Precipitation Inches	Integrated S Radiation, cal	Net Radi. cal/cm²		Relative Hum at Max. Te	Soil Tempera °F	
							Pos.	Neg.		2"	6"
1	81	34	261.0	0.45		592	292	74	18	54	55
2	69	36	124.4	0.27		336	179	76	14	55	55
3	73	38	352.0	0.38	TR	566	332	83	25	52	53
4	52	31	274.0	0.28		535	292	66	45	49	50
5	53	31	156.4	0.19		575	290	73	34	48	50
6	66	32	132.9	0.20		625	323	76	21	50	53
7	82	40	235.7	0.35		623	339	88	13	53	55
8	68	33	243.9	0.44		631	304	72	21	52	55
9	65	36	131.1	0.21		451	256	75	25	54	56
10	74	41	374.3	0.37		513	272	73	23	55	56
11	79	38	313.7	0.42		639	320	79	18	54	56
12	68	29	141.9	0.27		638	337	79	24	52	56
13	76	33	182.6	0.29		636	348	81	21	54	57
14	61	32	301.8	0.38		647	346	87	22	51	55
15	58	35	124.6	0.27		637	324	49	40	53	56
16	68	26	135.7	0.24		658	337	91	29	52	56
17	65	30	207.4	0.29		598	324	84	32	54	57
18	80	41	173.1	0.23		542	315	84	18	56	58
19	84	45	194.3	0.27		495	291	68	18	62	62
20	82	51	283.8	0.45		667	361	72	24	61	62
21	75	40	238.8	0.42		624	303	73	17	56	60
22	79	44	153.2	0.21		655	331	59	23	60	62
23	69	37	101.9	0.26		641	349	61	35	58	61
24	78	42	240.5	0.33		541	323	45	31	61	63
25	81	51	266.0	0.29		498	286	29	43	64	64
26	84	57	217.5	0.24		499	265	39	48	65	66
27	88	58	229.9	0.29		627	307	68	24	66	66
28	88	60	191.9	0.34		192	97	42	7	66	67
29	77	48	168.1	0.21		316	166	47	26	63	65
30	72	47	199.0	0.23		331	190	31	54	61	63

Bushland,
Texas

April
1974

(Contd.)

	Soil Moisture, inches total H_2O					
	0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1	2.97	3.45	3.39	3.45	3.40	3.25
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12	2.69	3.22	3.22	3.34	3.37	3.25
13						
14						
15						
16						
17						
18	2.63	3.12	3.15	3.27	3.37	3.24
19						
20						
21						
22						
23						
24						
25	2.52	2.95	3.03	3.16	3.26	3.18
26						
27						
28						
29						
30						

Bushlan
Texas

May
1974

Day	Maximum Temp. °F	Minimum Temp. °F	Wind Movement Miles	2' Evaporation Pan Inches	Precipitation Inches	Integrated Solar Radiation, [illegible] m^2	Net Radiation cal/cm^2 Pos.	Net Radiation cal/cm^2 Neg.	Relative Humidity at Max. Temp.	Soil Temperature °F 2"	Soil Temperature °F 6"
1	64	48	117.4	0.14	TR	418	192	45	61	61	63
2	72	48	135.8	0.16		715	337	79	41	60	62
3	90	46	255.5	0.43		683	359	69	8	64	65
4	70	41	159.7	0.21		563	197	62	44	64	66
5	75	45	142.2	0.06	1.59 1/	645	438	49	56	52	56
6	66	41	83.6	0.19		718	446	75	31	54	58
7	71	45	156.0	0.27		776	401	74	29	54	58
8	82	51	159.5	0.27		711	378	72	27	57	59
9	87	54	105.6	0.25		654	356	79	23	60	62
10	89	52	122.8	0.28		627	347	65	24	61	64
11	93	53	250.7	0.40		698	390	81	24	62	64
12	77	54	171.0	0.31		673	394	76	35	64	65
13	89	57	308.9	0.35		691	389	80	26	68	68
14	91	49	233.2	0.44		685	369	77	11	64	66
15	76	48	188.5	0.37		723	379	85	24	64	67
16	95	53	204.7	0.50		631	322	78	12	65	67
17	94	53	127.4	0.34		684	340	62	16	65	68
18	91	57	169.8	0.31	TR	652	372	65	19	69	70
19	91	62	223.9	0.30		654	407	70	25	70	72
20	91	64	366.1	0.49		611	340	65	31	72	72
21	83	49	190.8	0.37		731	347	95	14	66	68
22	79	47	100.8	0.31		617	271	75	17	66	69
23	88	47	111.1	0.32		571	260	73	14	67	70
24	91	58	139.6	0.28		376	244	31	21	70	72
25	77	55	185.9	overflow	2.30 2/	594	404	49	68	61	65
26	77	52	92.9	0.20		689	438	73	58	62	65
27	81	55	119.6	0.23		663	433	72	54	64	66
28	91	56	243.9	0.40		496	271	70	18	62	65
29	95	64	179.0	0.34		578	322	66	20	63	65
30	86	54	95.8	0.22		589	304	82	37	62	66
31	91	56	154.0	0.32		419	235	44	12	65	68

1/ some small hail
2/ hail up to 3 inches in diameter

Bushland,
Texas

(Contd.)

May
1974

	Soil Moisture, inches total H_2O					
	0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1						
2						
3	2.45	2.90	2.95	3.08	3.21	3.18
4						
5						
6						
7						
8						
9	3.45	3.20	3.05	3.13	3.22	3.19
10						
11						
12						
13						
14						
15						
16						
17	2.79	3.04	3.00	3.07	3.22	3.22
18						
19						
20						
21						
22						
23	2.61	2.93	2.94	3.06	3.18	3.19
24						
25						
26						
27						
28						
29						
30						
31	3.39	3.03	2.90	2.97	3.12	3.12

Bushland Texas

June
1974

Day	Maximum Temp. °F	Minimum Temp. °F	Wind Movement Miles	2' Evaporation Pan Inches	Precipitation Inches	Integrated Solar Radiation, cal/cm^2	Net Radiation cal/cm^2 Pos.	Net Radiation cal/cm^2 Neg.	Relative Humidity at Max. Temp.	Soil Temperature °F 2"	Soil Temperature °F 6"
1	72	49	138.5	0.24		536	313	66	62	62	66
2	81	50	119.6	0.19	0.22	556	362	40	37	62	65
3	78	55	193.9	0.26	0.50	-*	423	56	62	63	65
4	83	55	226.8	0.19	0.01	-*	265	76	55	63	65
5	83	56	141.5	0.22		642	396	62	47	63	66
6	91	62	135.3	0.29		598	334	54	19	67	69
7	81	52	153.4	0.27		507	298	42	38	66	68
8	80	55	211.1	0.19	0.08	678	413	45	28	66	68
9	79	50	295.8	0.54		725	416	76	8	62	66
10	77	51	107.2	0.25		702	372	70	27	64	67
11	86	54	229.2	0.49		716	383	69	19	66	68
12	83	53	145.8	0.28		622	347	52	39	67	70
13	82	57	165.0	0.24		572	299	62	45	69	71
14	90	58	118.9	0.28		678	342	58	21	70	71
15	94	59	80.1	0.28		666	323	34	19	71	73
16	96	61	125.1	0.49		678	366	49	20	73	75
17	86	60	179.7	0.33	0.47	629	378	33	42	70	73
18	96	60	147.9	0.34		697	384	53	19	70	72
19	96	61	92.9	0.29		705	368	59	20	72	74
20	98	67	174.3	0.41		712	378	66	22	74	76
21	94	66	225.3	0.45		700	362	66	28	74	76
22	98	66	187.6	0.37		617	335	61	26	76	77
23	89	63	147.3	0.35		627	352	47	47	76	77
24	84	56	160.1	0.34	0.13	459	274	43	53	74	76
25	76	53	99.5	0.23	TR	694	360	63	54	68	72
26	85	55	190.9	0.37		708	370	70	36	70	72
27	86	57	224.3	0.39		699	364	75	33	70	73
28	91	57	221.4	0.44		640	334	68	29	72	74
29	94	59	210.4	0.47		687	340	72	27	72	74
30	98	63	173.0	0.44	0.04	260	114	62	23	74	76

*Not measured

Bushland, Texas

(Contd.)

June
1974

	Soil Moisture, inches total H_2O					
	0-1'	1-2'	2-3'	3-4'	4-5'	5-6'
1						
2						
3						
4						
5						
6						
7	3.64	3.06	2.94	2.99	3.13	3.14
8						
9						
10						
11						
12	WHEAT HARVESTED					
13						
14						
15						
16						
17	3.53	3.05	2.95	3.03	3.18	3.16
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						

SOLAR RADIOMETER

MANNED SPACECRAFT CENTER

FORTRAN-FAP CODING FORM

PROGRAM ____________

CODED BY ____________

PUNCH ________ VERIFY ________ TABULATE ________ EXECUTE ________

BUSHLAND, TEXAS

UNIT	DATE	LAT	LONG	TIME	AIR MASS	3800	5000	6100	7457	8730	9420	10400
1007	102373			1240	1.50	52	47	44	32	24	[illegible]	[illegible]
1007	111073			12[illegible]	1.48	[illegible]	58	58	43	32	56	61
1007	11[illegible]373			114[illegible]	1.9[illegible]	71	[illegible]	58	[illegible]	4[illegible]		[illegible]
1007	121673			11[illegible]	[illegible]	60	80	66	54	[illegible]	92	2[illegible]
1007	010374			1140	2.05	5[illegible]	30	76	57	44		6[illegible]
1007	[illegible]12174			12[illegible]	1.71	[illegible]	[illegible]	[illegible]	[illegible]	42	75	75
1[illegible]	[illegible]74			1240	1.[illegible]	7[illegible]	[illegible]	[illegible]	60	44		70
1[illegible]	02267[illegible]			1240	1.47	74	57	10	58	42		[illegible]
1007	[illegible]74			1240	1.3[illegible]	74	[illegible]	[illegible]	5[illegible]	37		7[illegible]
1027	[illegible]			1[illegible]	1.2[illegible]	5[illegible]	52	7[illegible]	[illegible]	[illegible]		[illegible]
1007	[illegible]74			1240	1.1[illegible]	7[illegible]	98	[illegible]1	51	38		[illegible]
1001	[illegible]50[illegible]74			1240	1.08	71	75	1[illegible]	4[illegible]	[illegible]	77	7[illegible]
1007	[illegible]			1240	1.07	66	60	56	40	21	75	[illegible]
1007	061474			1156	1.15	6[illegible]	61	56	41	32	75	[illegible]

DATE MO/DAY/YR
XX XX XX

LAT } LONG } DEG/MIN/SEC
XX XX XX

TIME XXXX

AIR MASS X.XX

READINGS XX

RESTRICTIONS O

IF READING = 10

IF READING > 10

IF READING IN E.

(Contd.)

SOLAR RADIOMETER
MANNED SPACECRAFT CENTER
FORTRAN-FAP CODING FORM

UNIT	DATE	COMMENTS	SEQUENCE
1009	102373	C[illegible]	
1009	111073	[illegible] clouds mostly in South & East [illegible] / [illegible] Positions delayed until 12:25 (still light haze	
1004	11[illegible]973	Clear (9420 > 100)	
1007	131673	High thin clouds; clouds moving in from [illegible]	
1009	011394	Clear (snow cover on ground) (9420 > 100)	
1009	12174	Clear (Clouds on the south)	
1[illegible]	[illegible]7[illegible]	Clear (9420 > 100)	
1019	022674	Clear (9420 > 100)	
1007	031674	Light Haze (9420 > 100)	
1009	040374	Spotty Clouds (9420 > 100)	
1009	[illegible]174	Slight Haze (9420 > 100)	
1009	050974	Spotty clouds	
100[illegible]	[illegible]774	slight haze with some [illegible] in air	
1009	061474	Spotty clouds	

Appendix B

Ground Truth Data
for the

Bushland Test Site

Including

Yield

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

Irrigated Wheat Fields - John Kuehler

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
) 1010W1	Sturdy, planted Sept. 1	220 lbs anhydrous ammonia per acre. Applied in August. This is 82% N.	4 Irrigations 1. Sept. 2. Dec. and Jan. 3. Mar. 20 4. May 1 North half got only 3 irrigations.	31.8 bushels per acre. Harvested June 8-10.	Hail damage on May 26, produced from 40% loss at North end of field to 20% loss at south end of field.
2) 1050W1	same	same	4 Irrigations on above dates	44 bu. per acre, same harvest date.	7% loss same hailstorm

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

<u>Irrigated Wheat Fields</u> - Paul Schneiderjan

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1) 8010W1	Sturdy	150 lbs of actual N per acre. Applied 8/1	4 irrigations Sept., Jan., April, May	39 bu/A	
2) 9010W1	"	"	3 - Sept., Jan., April	29	
3) 8040W1	"	"	4 on south 2/3. 3 on north 1/3. See above dates	35 average	27% hail loss on 5/26
4) 8051W1	"	"	4 waterings same dates	38	
5) 8052W1	"	"	watered sooner on north side	18	green bug infestation in south and west portions of fi
6) 9060W1	"	"	4 on above dates	42	
7) 9080W1	a strip of sturdy 150-40" rows wide, less than 1/4 of field. (lighter tan in color) Rest Palo Duro.	"	4 waterings	40 bu/A	

Notes: Grazed cattle on all fields Nov. 1st to Jan 1st. May 26th hail produced 18% overall loss, was more severe at north end of farm.

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

Irrigated Wheat Fields - Johnny Sluder

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1) 2010W1	2 strips of hybrid wheat running N-S 30 yds and 40 yds wide at E end of field. Rest is Tascosa. All fields planted 9-15 to 10-15	Except for field No. 3, all received 250 lbs per acre of anhydrous amonia. This source has 82% N. Applied in July.	4 on all - 2 fall & 2 spring	55 bu/A	
2) 3010W1	Tascosa & Palo Duro	See above	See above	45	
3) ~~0~~040W1	Palo Duro	10 tons manure per acre + 200 lbs slurry mix of 32% N per acre.	"	40	
4) 3060W1	Concho	See field No. 1	"	40	
5) 2030W1	Tascosa	"	"	40	Sprayed on 3/ with 2-4, D Butyltype
6) 2060W1	"	"	"	40 (late)	
7) 2070W1	Concho	"	"	50	
8) 3100W1	Palo Duro	"	"	38	
9) 5090W1	Concho	"	partially irrigated	12 to 40 bu/A 28 average	
0) 5052W1	Tascosa	"	See No. 1	35	
1) 5080W1	Concho	"	"	45	

Planted between 9/15 and 10/15. Qualified for a 30% hail adjustment on entire farm as a result of May 24 storm. Damage ran as high as 57%. Had a heavy greenbug infestation. Sprayed on Oct. 20 and Nov. 20. Mr. Sluder is one of the few farmers in the area to use other than a 40 inch row spacing. He has gone to a 36" row in order to increase his plant population per acre. His yields consistently are among the highest in the area.

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

<u>Irrigated Wheat Fields</u> - Max Rarick

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1) 6020W1	Planted in October. Mixture of sturdy & Concho.	150 lbs anhydrous amonia applied in Aug. (82% N)	One irrigation in Spring - Jan or Feb	9.9 bu/A	
2) 6061W1W4	"	"	"	19.4	
3) 6110W1W4	"	"	"	22.7	

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

<u>Irrigated Rye Fields</u> - Central Cattle Co.
John Hardaway, foreman

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1) 10010R	Elbon rye	35 tons manure per acre in 1971. 150 lbs anhydrous amonia (86% N) 1972 or 1973. In 1974 applied 200 lbs anhydrous preplant.	6 irrigations	Grazing Only	

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

<u>Non-Irrigated Wheat Fields</u> - John Kuehler

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1D) 4060W2	Volunteer Wichita	None	None	None	Plowed under

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

Non-Irrigated Wheat Fields - Don Walton

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1D) 7020W3		None	None	None	Plowed under in April
2D) 7030W2		"	"	"	"

REMOTE SENSING
BUSHLAND WHEAT PROJECT - 1974

Non-Irrigated Wheat Project - Max Rarick

Owner & Number	Variety	Fertilizer	Irrigation	Yield	Other
1D) 6010W3	Used mixture of sturdy & concho. Saved seed back from harvest. Planted in Oct.	150 lbs actual N per acre. Applied in August.	watered once in March	20 bushels per acre	
2D) 6061W3W4	same as above	same	no water	plowed up	
3D) 6070W3	"	"	one watering in March	12.8 bu/A. Had not finished harvesting by 7-2-74	had a lot of weeds

Appendix C

Sorghum Plant Stress

Data for

July and August 1973

Following is a summary of soil and plant measurements made in connection with the microwave studies on sorghum at the Brazos bottom field site.

A. SOIL MOISTURE

	July 19	July 25	August 28	August 30
Surface 1/	11.1	55.3	36.2	9.6
10 cm 2/	33.0	38.1	33.5	32.1
20	30.9	36.1	32.1	30.7
30	30.0	35.1	31.1	29.4
40	29.3	35.8	30.5	29.3
50	29.3	36.5	32.6	31.5
60	32.3	37.9	34.5	32.5
70	33.9	-38.0	35.0	33.7
80	34.9	39.0	35.9	35.6
90	36.1	39.3	37.0	36.1
100	37.6	38.8	38.3	36.6

1/ Surface moisture content determined gravimetrically.

2/ Depth below surface. Moisture content determined with neutron probe.

B. PLANT DENSITY AND MOISTURE CONTENT 1/

	July 19	July 25	August 28 2/
No. Plants	24	24	-
Fresh wt.	2930 g	3839 g	2111 g
% H_2O	71.3	69.4	56.0

1/ Values representative of a 5 ft. section of row spaced 40" apart.

2/ Plots had been sprayed with a dessicant. At least 80% of the leaves were dried and brown.

C. SOIL TEMPERATURE

	July 19				July 25				August 30
Depth (cm)	1020	1305	1450	1615	0930	1230	1345	1510	1300
5	26.6	30.4	32.5	33.6	26.5	31.1	33.2	34.5	49.9
10	26.6	27.3	30.1	31.4	28.3	30.3	31.5	32.5	-
15	27.5	29.2	30.7	30.7	-	30.7	32.6	32.8	40.0
20	26.0	26.9	28.8	30.7	29.9	30.2	30.8	31.0	-
30	28.0	28.0	28.9	29.2	31.4	30.7	32.8	32.1	41.7
45	27.7	27.7	28.5	28.2	30.9	30.7	32.6	30.7	41.7
60	27.2	27.7	28.0	28.0	30.2	30.4	31.1	31.1	38.6
75	26.5	27.2	27.7	27.8	29.2	29.7	30.4	30.2	39.5

Appendix D

Lysimeter Data

for

Study of Moisture Stress

GRAIN SORGHUM EVAPOTRANSPIRATION AND WATER USE EFFICIENCY UNDER TRICKLE IRRIGATION[1]

by

T. A. Howell and E. A. Hiler[2]

Water use efficiency (WUE) as defined by Viets (1962) is the crop yield, Y, (dry matter or marketable yield) produced per unit volume of water used in evapotranspiration, E_t. As discussed by Hillel (1972), WUE involves two interpretations: (1) the technical (or engineering) aspect of minimizing wastes of water, e.g., utilizing practices which improve water conveyance efficiency, water application efficiency, and water distribution efficiency and (2) the agronomic aspect of maximizing crop yield per unit of crop water use. The latter aspect of WUE has become increasingly interesting due to recent findings of many research investigations regarding effects of trickle and subsurface irrigation on WUE (Cole, 1971). These findings have indicated that crop water requirements can be substantially decreased while maintaining approximately equal yields when using trickle and subsurface irrigation compared to so-called "conventional methods". Yet few replicated, well-instrumented experiments have been conducted in which both crop yield and crop water use were measured under trickle irrigation (Hiler and Howell, 1973).

Maximizing WUE as pointed out by Viets (1966) may not be desirable since crops grown on dryland frequently use water more efficiently than well-watered crops, but at much lower levels of production. Maximum yields are seldom desirable from an economic viewpoint since other resources - fertilizer, disease control, pest control, labor, etc.- are not utilized efficiently. However,

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[1]Approved as Texas Agricultural Experiment Station Paper No. ________

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an "optimum" WUE - maximum yield per unit of water subject to local constraints of water, labor, etc. - is a desirable tool for water planners in assessing future water requirements.

WUE can be increased by (1) increasing yield and maintaining equal water use or (2) maintaining equal yield and decreasing water use. Yield can be increased by better methods of pest and disease control, improving supplies of sunlight and carbon dioxide to the leaves. Some of these practices will invariably also cause some change in the water use pattern which will also directly affect WUE. Hillel and Guron (1973) state that it appears more promising to attempt to increase WUE by increasing crop yields than by decreasing evapotranspiration, since plants growing in the field are subject to an externally imposed evaporative demand. This statement is valid for well-watered crop regimes but does not fully explore the possible implications of limited irrigation in regions of short and/or costly water supplies.

Several crop species have demonstrated "drought tolerance" in certain stages of the crop development (Salter and Goode, 1967, Hiler and Clark, 1971, and Jensen, 1968). Thus there appears to be a potential application for limited irrigation at specific growth stages of certain crops to improve WUE by limited irrigation, thereby decreasing the evaporation and the yield but not in a direct proportional relationship. The purpose of this paper was to test this hypothesis. Specific objectives were as follows:

(1) to determine the evapotranspiration and yield of grain sorghum grown under a frequent but limited irrigation regime:

(2) to evaluate the effects of frequent, limited irrigations at specific growth stages on grain sorghum yield; and

(3) to utilize an existing water balance model (Richardson and Ritchie, 1973) to separate the soil and plant evaporation components and evaluate their effect on water use efficiency.

DESCRIPTION OF EXPERIMENT

The experiment reported herein was conducted in 1972 and 1973 utilizing field lysimeters. Certain aspects of the 1972 experiment were discussed previously (Hiler and Howell, 1973). Nine lysimeters with undisturbed cores of Travis fine sandy loam soil were utilized in 1972, and 24 of the same type of lysimeters were utilized in 1973. This soil consisted of a layer of fine sandy loam in the A-horizon to a depth of 45 cm with an available water holding capacity of 0.12 cm per cm of depth and a red sandy clay soil in the B-horizon with an available water holding capacity of 0.22 cm per cm of depth. The lysimeters were 90 cm in diameter and 180 cm deep.

The experimental arrangement allowed three replications of each treatment. The area outside the lysimeters was used as a buffer area to simulate a field condition. A movable shelter, automatically actuated by rainfall, protected the lysimeters from rain. A detailed description of the installation has been given by Hiler (1969).

Wind speed, dry-bulb temperature, dew-point temperature and net radiation were measured above the crop canopy. Wind speed was measured by cup anemometers at heights of 1, 2, and 3 m above the ground. Dry-bulb temperature was measured at 1 and 2 m above the ground with aspirated thermocouples. Dew-point temperature was measured at 1 and 2 m above the ground with lithium chloride dew-point hygrometers. Net radiation was measured by a miniature net radiometer similar to that described by Fritschen (1965) at a height of 1.5 m above the ground. These meteorological measurements were used to estimate the potential evapotranspiration from the crop (Van Bavel, 1966 and Penman, 1948). Class A pan evaporation was measured in a nearby weather station.

The soil-water pressure potential was measured in each treatment at 15- and 30-cm depths with tensiometers. Also, the center lysimeter of each treatment

was instrumented for psychrometric determinations of soil water potential at depths of 10 and 20 cm and for pressure potential determination by tensiometers at 60- and 90-cm depths. The soil water content in each lysimeter was determined by the neutron method (Van Bavel, et al., 1963) to a depth of 105 cm in 15-cm increments.

Grain sorghum (Sorghum bicolor (L.) Moench. cv. 'Oro') was planted on April 14, 1972 and on April 13, 1973 and was harvested on July 25, 1972 and on August 3, 1973. Double rows 25 cm apart were planted across the center of each lysimeter. Plant populations were uniformly thinned to 18 plants per lysimeter (222,000 plants/ha). Each lysimeter received applications N, P, and K at rates of 67 kg/ha each prior to planting; 67 kg/ha of N was also added at the 4- to 6-leaf stage of plant development. All lysimeters were irrigated prior to planting in the amount necessary to replenish the top meter of soil to "field capacity".

The treatments used in 1972 were as follows: (1) Trickle (1.1)--Control; (2) Trickle (0.7); and (3) Trickle (0.4). The irrigation amount for the Trickle (1.1) treatment was determined as 1.1 times the water depletion in that treatment as measured by the neutron method. The irrigation amount for the Trickle (0.7) treatment was 0.7 times the measured water depletion in the Trickle (1.1) treatment while that for the Trickle (0.4) treatment was 0.4 times the depletion in the Trickle (1.1) treatment.

The treatments used in 1973 were as follows:

1. Irrigated in the amount of <u>1.1</u> times the measured evaporation losses as determined by the water balance of the lysimeters and soil water content measured by the neutron method (Control);

2. Irrigated in the same amount as treatment 1 during 2 of the 3 growth stages of the crop, and irrigated in the amount of <u>0.4</u> times the measured evaporation losses in treatment 1 during the <u>third growth stage</u> (III-0.4);

3. Same as treatment 2 except that the irrigation amount was <u>0.4</u> during the <u>second growth stage</u> instead of during the third growth stage (II-0.4);

4. Same as treatment 2 except that the irrigation amount was 0.4 during the first growth stage instead of during the third growth stage (I-0.4);

5. Same as treatment 2 except that the irrigation amount was 0.1 during the third growth stage instead of 0.4 (III-0.1);

6. Same as treatment 5 except that the irrigation amount was 0.1 during the second growth stage instead of during the third growth stage (II-0.1);

7. Same as treatment 5 except that the irrigation amount was 0.1 during the first growth stage instead of during the third growth stage (I-0.1); and

8. Irrigated in the amount of 0.32, 0.64, and 0.42 times the measured evaporation losses in treatment 1 during growth stages one, two, and three, respectively, (SDI).

The growth stages utilized were similar to those of Lewis, et al., (1974), and were as follows:

Growth Stage No.	Description
1	Late vegetative to early reproductive stage
2	Boot to bloom stage
3	Milk to soft dough stage

Growth stage one included stages 2, 3, 4 and part of stage 5 as defined by Vanderlip and Reeves (1972). This stage started on May 22, 28 days after emergence, and ended on June 9 (19 days later) in 1972, and started on May 23, 30 days after emergence, and ended on June 8 (17 days total length) in 1973. Growth stage two included stages 4, 5, and 6 as given by Vanderlip and Reeves (1972). This stage started on June 2, 39 days after emergence, and ended on June 22 (21 days total length) in 1972, and started on June 4, 42 days after emergence, and ended on June 29 (26 days total length) in 1973. Growth stage three included stages 6 and 7 as defined by Vanderlip and Reeves (1972). The third stage began on June 20, 57 days after emergence, and ended on July 10 (21 days total length) in 1972 and began on June 22, 60 days after emergence and ended on July 16 (25 days total length) in 1973.

Each treatment in 1972 and 1973 was irrigated three times a week (Monday, Wednesday, and Friday) during the irrigation season. The irrigation amount

was determined as

$$I_i = F\ (W_s - W_i)$$

where I_i = the irrigation amount, mm,

F = the treatment multiplication factor,

W_s = the "field capacity" soil water content, taken as 215 mm, and

W_i = the measured profile soil water content, on day i, mm.

The irrigation systems consisted of 1.58-cm (1/2 in. nominal) I.D. black polyethylene pipe with two "Triklon" emitters per lysimeter. This emitter is a coiled microtube approximately 2.44 m in length with a 0.89-mm I.D. (0.035 in.) which discharged approximately 12.9 cu cm per min (0.20 gph) at 0.69 bar (10 psi) The irrigation water had an electrolyte concentration of 450 ppm, a sodium-adsorption-ratio of 40, and an electrical conductivity of 700 μmhos/cm; it was filtered with a cartridge filter. A timer was set to operate a solenoid valve on the irrigation system for each treatment to apply the calculated irrigation amount. The system application rate per lysimeter was 0.24 cm per hr with an estimated application accuracy of ±0.05 mm per irrigation. Emitter flow rates were checked weekly.

Crop height and leaf area index were evaluated to describe the growth of the crop. Crop height was measured twice weekly in each lysimeter. From leaf samples taken throughout the season, leaf length times leaf width was statistically correlated to leaf area with a least-squares linear regression analysis.

Leaf temperature was measured daily with an infrared radiometer in both years. Measurements of leaf temperature were taken on two well exposed leaves in each lysimeter at 1 p.m. CDT. Leaf water potential was measured daily between 1 and 2 p.m. CDT and on selected mornings between 6 and 7 a.m. CDT using the pressure chamber apparatus (Scholander, et al., 1965). The leaf samples were prepared similar to the method of De Roo (1969). Since this method is a

destructive sampling technique, only one measurement per treatment was taken at any one time. Measurements were made only on the upper exposed leaves in the canopy (second to fifth leaf from top). Leaf diffusion resistance was measured on selected days with a diffusion porometer (Van Bavel, et al., 1965).

Total water use for all treatments in 1972 and 1973 was determined by the water balance method. Drainage was calculated from the amount of water pumped from the lysimeters at the bottom. Lysimeters were pumped weekly and electrical conductivity of the effluent was measured. Storage losses were determined from the change in water content profile between planting and harvesting. Irrigation amount was the total of all water added to the lysimeters between planting and harvest. The total water use was equal to irrigation amount plus storage losses minus drainage amount.

Grain yield was determined for each lysimeter by harvesting and threshing all heads in the lysimeter. The moisture content of the grain was determined and all yields were adjusted to 14-percent moisture content (wet basis).

RESULTS AND DISCUSSION

Evaporation and Seasonal Water Use

The cumulative values of the net radiation (equivalent evaporation depth assuming 583 cal. g^{-1}), Class A pan evaporation, Penman and Van Bavel potential evaporation estimates, and evapotranspiration from the Control treatment (1.1) for 1972 and 1973 are given in Figure 1. The three estimates of potential evaporation were systematically different, with Class A pan giving the largest values followed by the Van Bavel and Penman methods in that order. The Class A pan data in 1972 contained 22 days of missing data due to equipment failure; thus after the 170th day, the cumulative amounts shown are incorrect but the evaporation rates depicted by the slope of the line are valid. The net radiation received in 1973 was on the average less than in 1972, and this

might have limited potential photosynthesis during critical periods in 1973. Total evapotranspiration in Control treatments (1.1) was 522 mm in 1972 and 478 mm in 1973 as shown in Figure 1. These results are similar to those reported for well-watered grain sorghum (Ritchie and Burnett, 1971, Hanks, et al., 1969, Jensen and Sletten, 1965).

The roughness length, Z_o, was assumed equal to 20 mm for all calculations in Van Bavel's equation. Additionally, Z_o was assumed to be a function of wind speed above the canopy (Szeiz, et al., 1973); this resulted in an underprediction of monthly potential evaporation (compared to the Z_o = 20 mm case) of less than 20 mm during the months of May through July while it overpredicted by as much as 42 mm during April (a period of essentially bare soil).

Considering the slopes of the lines in Figure 1 (evaporation rate), Van Bavel's method appears to be a better predictor of potential evaporation rates than was Penman's method after the necessary crop canopy development (Ritchie and Burnett, 1971), which occurred on day 152 in both years. This conclusion is opposite to that reached by Richardson and Ritchie (1973) in a similar climate in Central Texas. The lysimeters in our study were subject to local advection, even though a border area was maintained, and our measurement accuracy did not approach that of Ritchie and Burnett (1968). However, since our data exhibited similar trends in both years and considering reported measurement accuracies for our method (Van Bavel and Stirk, 1967) for time periods on the order of several days, we feel that our conclusion is valid.

Cumulative values of the total water loss (includes both evapotranspiration and drainage) for each treatment in 1972 and 1973 are given in Figure 2. The evapotranspiration of the treatments was largely determined by the irrigation quantity. This is due primarily to the restricted root zone and limited water holding capacity in this soil type. The water use data indicated that 90 percent

or more of the water used as measured on a 105-cm profile occurred above the 30 cm-depth in all the treatments in 1973. Critical values of soil water potential can develop in this type of soil in short periods of time (5 to 7 days) when the plant water use is large (7 to 10 mm/day).

Plant Measurements

Measurements of leaf surface resistance (R_s) and leaf water potential (ψ_ℓ) were taken three times weekly (Tuesday, Thursday, and Saturday) in 1973 on three irrigation treatments at approximately 1:00 to 4:00 p.m. CDT. The treatments measured were the Control (1.1), 0.4, and 0.1 treatments at respective growth stages. Only one lysimeter per treatment was sampled. Four well-illuminated, fully-expanded leaves were selected for R_s measurements and one leaf per treatment for the ψ_ℓ measurement. The leaf was shaded for 10 seconds prior to attaching the cup and both the cup and leaf were shaded during the measurement. Figure 3 shows that the only significant difference in R_s between treatments occurred in stage I where treatment I-0.1 experienced partial stomatal closure. This was verified by visual observation of wilting in treatment I-0.1, as opposed to I-0.4 and Control which showed no external signs of stress. It is interesting that this wilting and partial stomatal closure of I-0.1 occurred at a relatively high ψ_ℓ (-13 to -16 bars) and that the ψ_ℓ was not significantly different than other treatments which experienced little or no stress. With the exception of R_s in the I-0.1 treatment there was essentially no difference between treatments in R_s (Figure 3) or in ψ_ℓ throughout the remaining growth stages (stages II and III). It was evident that water never became limiting enough to affect either ψ_ℓ or R_s and any differences in yield between treatments was therefore due to some other factor than stomatal closure (the only exception to this would be treatment I-0.1 where differences in yield might partially be due to hydroactive closure of stomates during

stage I). An increasing trend of R_s in all treatments was observed during the latter stages of growth (Figure 3). This suggests a possible aging effect of the leaves.

The results of measurements of ψ_ℓ and leaf temperature in 1972 are given by Hiler and Howell (1973). The effects of the 1973 treatments on leaf temperature were small and never exceeded 1°C.

Table 1 gives the measured values of leaf area index (LAI) in 1972 and 1973. The maximum variance in the LAI data was ±0.49 which was due to the small sample size. Therefore, some of the indicated differences in Table 1 are not significant. However, the treatment influence was apparent in most instances. Possibly, the induced water stress affected the nutrient balance of the plants more than the plant water balance (Phene, 1974). In some cases "yellowing" of the leaves was visible shortly after the treatment initiation, and in other cases early senescence resulted. Only small differences in crop height were observed. Only water deficits in stage I affected crop height in 1973. Treatments I-0.4 and I-0.1 were reduced 8 and 18 cm, respectively, as compared to an average crop height of 103 cm for the Control (1.1).

Yield and Water Use Efficiencies

The yield and water use efficiency results are given in Table 2. Analyses of variance were performed on the yields; in all cases, variance between treatments was significant at the one percent level and variance among replications was "not significant." Test of difference between treatment means was done by Duncan's multiple range test. The irrigation values in 1972 were slightly modified from previous work (Hiler and Howell, 1973) to account for preseason irrigations. The 1972 results indicated an increase in WUE with a decreasing irrigation quantity. Apparently, due to the 1972 treatments, only the latter growth stage (milk to soft dough) was stressed while sufficient soil moisture

in storage was maintained during the first two growth stages. These conclusions were verified by the 1973 results in which only water deficits prior to the milk to soft dough stage (stage III) affected yield and WUE to a large extent. However, the SDI treatment in 1973 produced the greatest WUE (see Hiler, et al., 1974, for a discussion of the SDI concept). This treatment was depleted at a variable rate, but maintained adequate soil water until the third growth stage. The above increases in WUE resulted, however, in lower production (less marketable yield). These trends are similar to results of Bucks, et al., (1973), Bucks, et al., (1974) and Patterson (1972) with other crop species. The Control treatment yield in 1973 was slightly less than in 1972; this could have been caused by the reduced net radiation received in 1973 (Figure 1).

The soil water balance model of Richardson and Ritchie (1973) and Ritchie (1972) was utilized to calculate the evapotranspiration during the growing season and to calculate separately the soil and plant evaporation components. Climatic data, beginning soil water content, leaf area index, irrigation quantities, and physical soil constants were required in the model. Details of the model are given by Richardson and Ritchie (1973).

Figure 4 shows comparisons of the results of the model calculations and the actual measured soil water content. The calculated values were within ±20 mm of the measured data on 95 percent of the days in 1973 and on 89 percent of the days in 1972. The correlation coefficient of calculated and measured soil water for 1973 was 0.91, and for 1972 it was 0.97. Most errors were near the accuracy of the soil water measurement. Table 3 gives the calculated water use for each treatment. Figure 5 shows the relationship between the calculated evapotranspiration and total losses and their measured values. The largest error was 17.5 percent in the evapotranspiration and 10 percent in the total water loss. Based on previous results, the model accuracy could be increased by using the Van Bavel method to estimate potential evaporation estimates. For the plant

and soil evaporation components given in Table 3, the ratio of soil evaporation to evapotranspiration (E_s/E_t) varied from maximum of 0.42 to minimum of 0.26. Using the calculated plant evaporation (E_p), water use efficiencies based solely on plant transpiration are presented also in Table 3. Those values show that only water deficits in growth stages I and II caused reductions in water use efficiency of grain sorghum production.

CONCLUSION

Evaluating the effect of limited irrigation on grain sorghum production has been of interest to many researchers, especially in Texas (Bonnen, et al., 1952, Swanson and Thaxton, 1957, Newman, 1960, Jensen and Sletten, 1965, Musick and Dusek, 1969 and 1970, Shipley and Regier 1970, and Lewis,et al., 1974). Most field experiments were subject to local rainfall patterns and deficiencies in measurement of crop water use which confounded many direct conclusions of that research. Yet the trend is apparent; grain sorghum is tolerant to limited "water deficits" at specific growth stages. The degree of the tolerance as reflected by the crop yield depends on the timeliness of certain rainfall or irrigations. The WUE can be increased, as compared to a well-watered control treatment, by allowing selected crop growth stages to be water-deficit periods while adequately irrigating the crop during certain "critical" periods of crop development.

This research demonstrates a potential for increasing WUE of grain sorghum by utilizing trickle irrigation to apply frequent, but small irrigation quantities and limiting these applications according to the stage of plant development. The findings of this research indicate that water deficits which occur before the milk to soft dough stage of grain sorghum development can reduce yield and water use efficiency. However, careful regulation of the irrigation quantity to minimize water deficits during those periods can increase

water use efficiency. Stage II (boot to bloom) is the most critical period. Utilizing an existing soil water balance model to determine plant transpiration further reinforced this conclusion when the yield per unit of transpired water was computed.

Utilizing the concepts of Jensen (1968) or Hiler and Clark (1971) to quantify the effects of water deficits on crop yields in combination with existing evapotranspiration models (Jensen et al., 1971 and Richardson and Ritchie, 1973), the optimum irrigation scheduling can be determined to maximize either WUE or yield. This work is in progress and will be the subject of a future paper.

ACKNOWLEDGMENTS

The leaf surface resistances and leaf water potential measurements and analysis were made by Mr. Steve Davis and his contribution is gladly acknowledged.

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TABLE 1. Leaf area index values for 1972 and 1973 growing season.

1972 TREATMENTS				1973 TREATMENTS								
DATE	1.1	0.7	0.4	DATE	1.1	I-0.4	II-0.4	III-0.4	I-0.1	II-0.1	III-0.1	SDI
May 16	0.47	0.49	0.78	May 16	0.32	0.50	0.25	0.35	0.27	0.22	0.25	0.32
May 23	1.23	1.27	1.55	May 22	1.12	1.45	0.95	1.18	0.82	0.68	0.92	0.84
May 30	2.35	2.56	2.88	May 29	2.39	2.35	1.74	2.32	1.57	1.66	2.14	1.91
June 6	3.93	4.02	3.87	June 5	3.81	3.48	2.66	3.29	2.19	2.75	4.11	3.30
June 13	4.77	4.46	3.96	June 12	4.98	4.46	4.05	4.92	3.04	4.09	4.31	4.99
June 20	4.73	4.74	3.92	June 19	5.12	4.21	4.09	5.05	3.44	4.69	4.28	5.01
June 27	4.58	4.44	3.94	June 26	5.15	4.46	4.04	5.08	3.64	4.45	4.53	4.90
July 3	4.65	4.05	3.17	July 3	4.89	4.27	3.62	4.38	3.51	3.89	4.23	4.76
July 11	4.48	3.20	3.04	July 10	4.46	4.04	3.52	3.77	3.49	3.45	3.64	4.35
July 18	4.12	2.99	2.66	July 17	3.35	3.63	2.84	2.81	3.54	3.10	3.01	3.20

TABLE 2. 1972 and 1973 yield, water use and water use efficiency results.

YEAR	TREATMENT	DRY MATTER YIELD DMY kg ha^{-1}	GRAIN YIELD[1] Y kg ha^{-1}	IRRIGATION I mm	DRAINAGE D mm	EVAPOTRANSPIRATION E_t mm	TOTAL LOSSES TL mm	WATER USE EFFICIENCY kg ha^{-1} mm^{-1} Y/E_t	Y/I
1972	1.1 (Control)	----	9,209 a[2]	537	28	522 a	550	17.7	17.1
	0.7	----	7,837 ab	351	35	366 b	401	21.4	22.3
	0.4	----	6,743 b	221	32	285 c	317	23.7	30.5
1973	1.1 (Control)	16,245	8,650 a	540	58	478 a	536	18.1	16.0
	I-0.4	15,770	7,880 ab	516	81	470 a	551	16.8	15.3
	I-0.1	14,036	6,910 c	378	35	378 c	413	18.3	18.3
	II-0.4	12,940	5,898 d	388	36	384 c	420	15.4	15.2
	II-0.1	11,972	5,196 d	370	32	390 c	422	13.3	14.0
	III-0.4	15,652	8,240 a	407	37	436 ab	473	18.9	20.2
	III-0.1	14,621	6,890 b	362	17	402 bc	419	17.1	19.0
	SDI	15,002	7,272 bc	239	37	345 d	382	21.1	30.4

[1]Grain yield corrected to 14 percent moisture content wet basis.

[2]Differences between means followed by the same letter are not statistically significant at the 0.05 level by the Duncan multiple range test.

TABLE 3. Comparison of measured and calculated water use data.

Year	Treatment	MEASURED		CALCULATED				Water Use Efficiency Y/Ep kg ha-1 mm-1
		Evapotranspiration Et mm	Total Losses TL mm	Evaporation		Evapotranspiration Et mm	Total Losses TL mm	
				Plant Ep mm	Soil Es mm			
1972	1.1 (Control)	522	550	320	137	457	604	28.8
	0.7	366	401	296	134	430	438	26.5
	0.4	285	317	191	136	327	327	35.3
1973	1.1 (Control)	478	536	321	124	445	570	26.9
	I-0.4	470	551	323	127	450	566	24.4
	I-0.1	378	413	293	118	411	426	23.6
	II-0.4	384	420	295	128	423	437	20.0
	II-0.1	390	422	269	133	402	420	19.3
	III-0.4	436	473	311	130	441	480	26.5
	III-0.1	402	419	261	130	391	439	26.7
	SDI	345	382	238	111	349	350	30.5

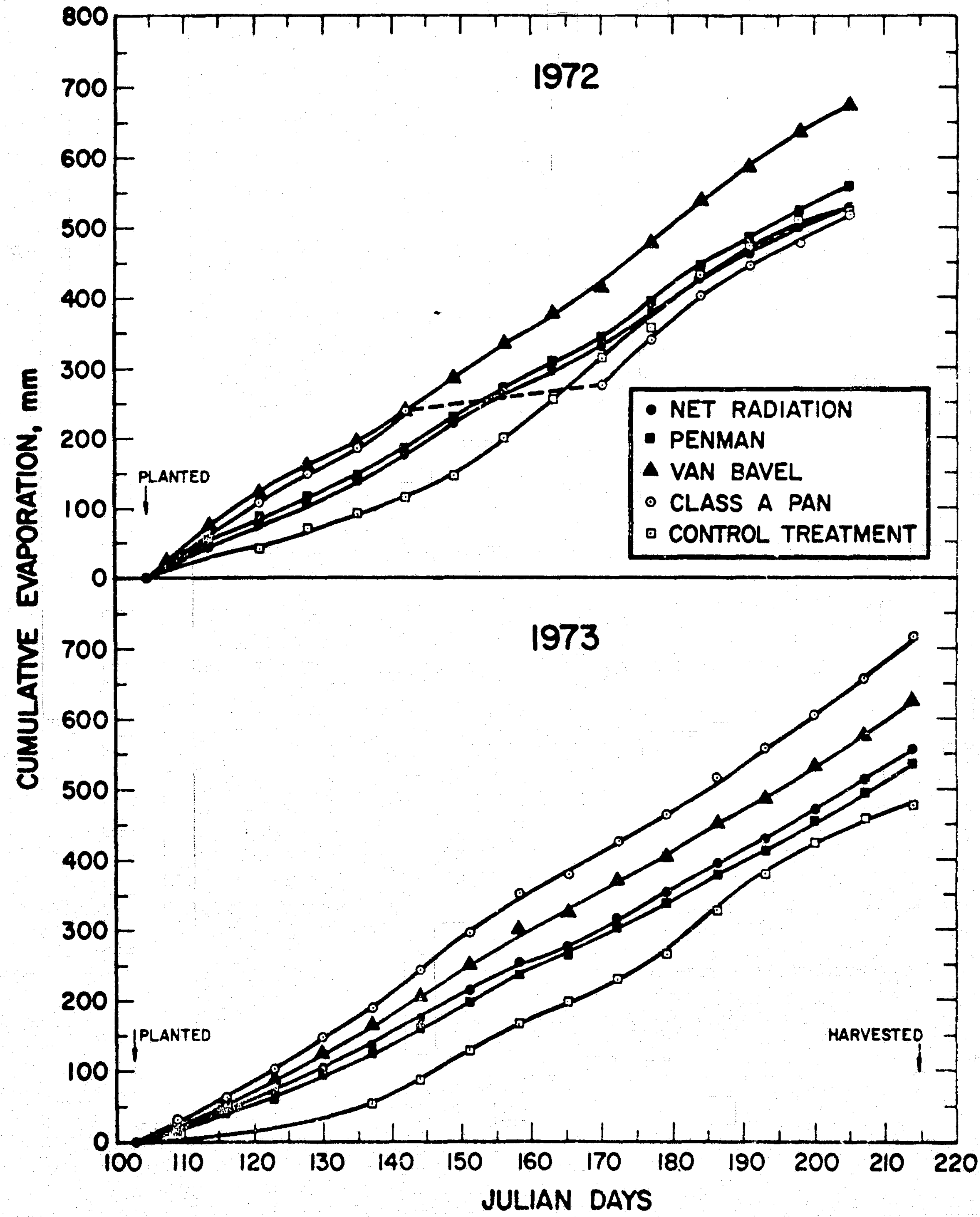
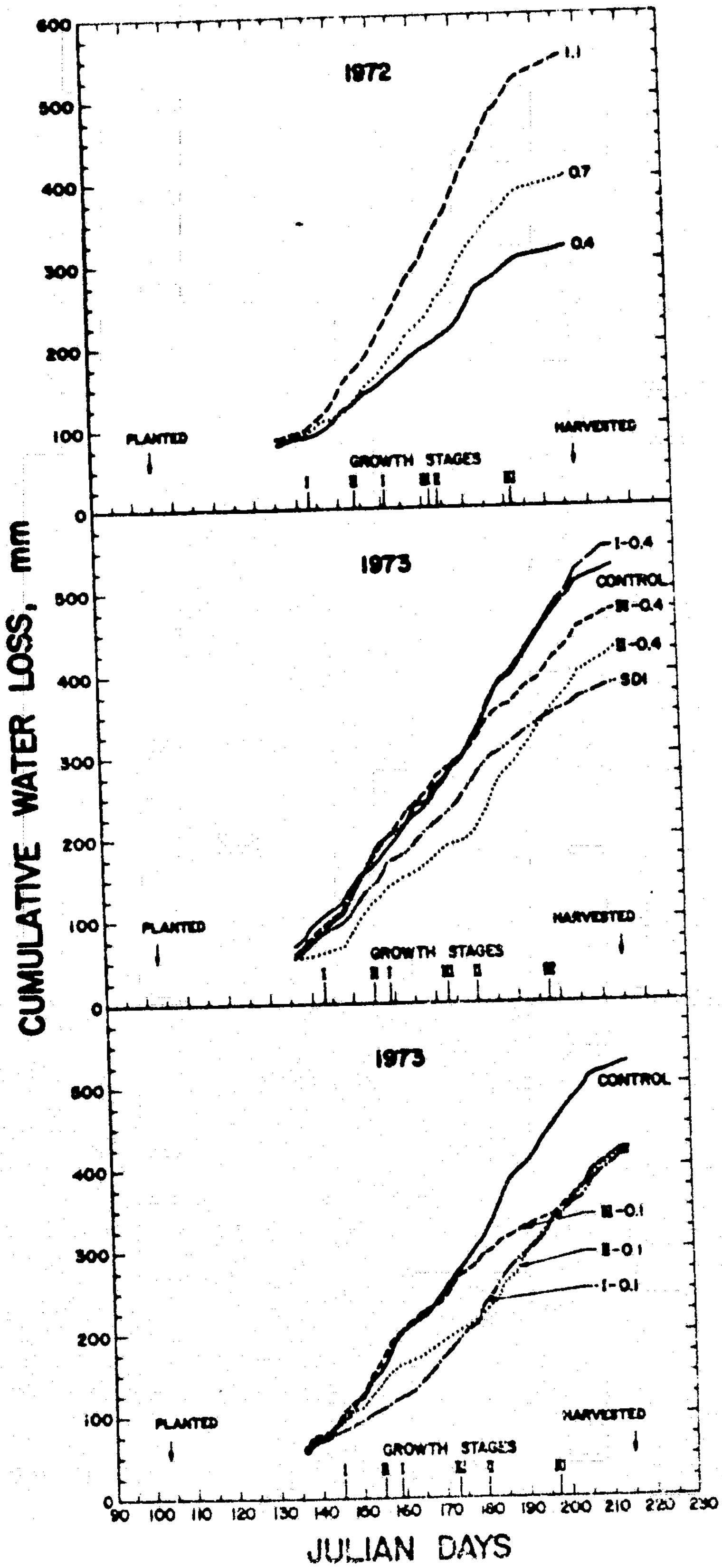


Figure 1. Cumulative net radiation (equivalent evaporation depth), Class A pan evaporation, Penman and Van Bavel potential evaporation estimates, and measured evapotranspiration from the Control treatment (1.1).

Figure 2. Cumulative water loss in each treatment.



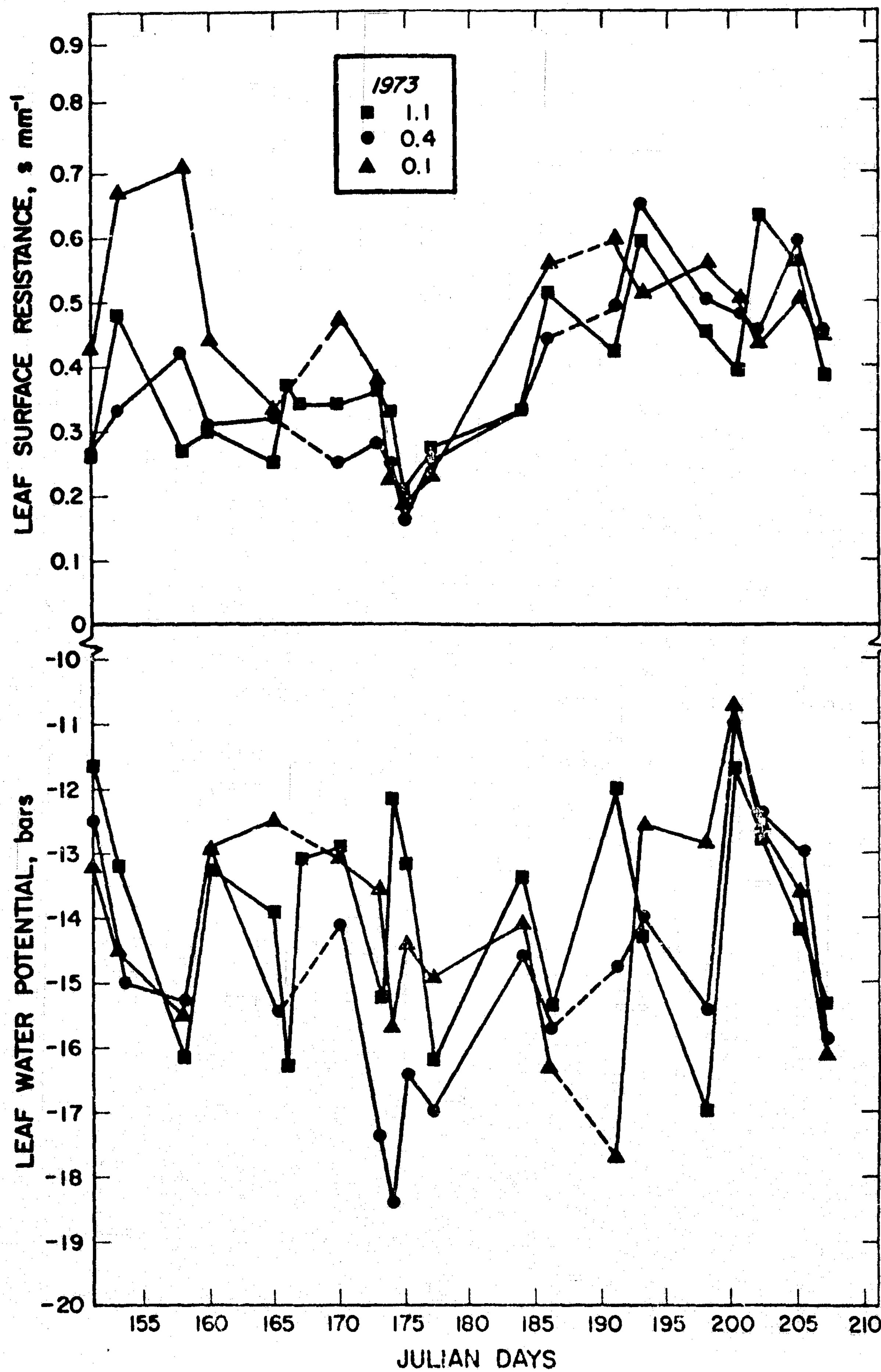


Figure 3. Leaf surf[illegible] resistance and leaf water [illegible] throughout 1973 [illegible]

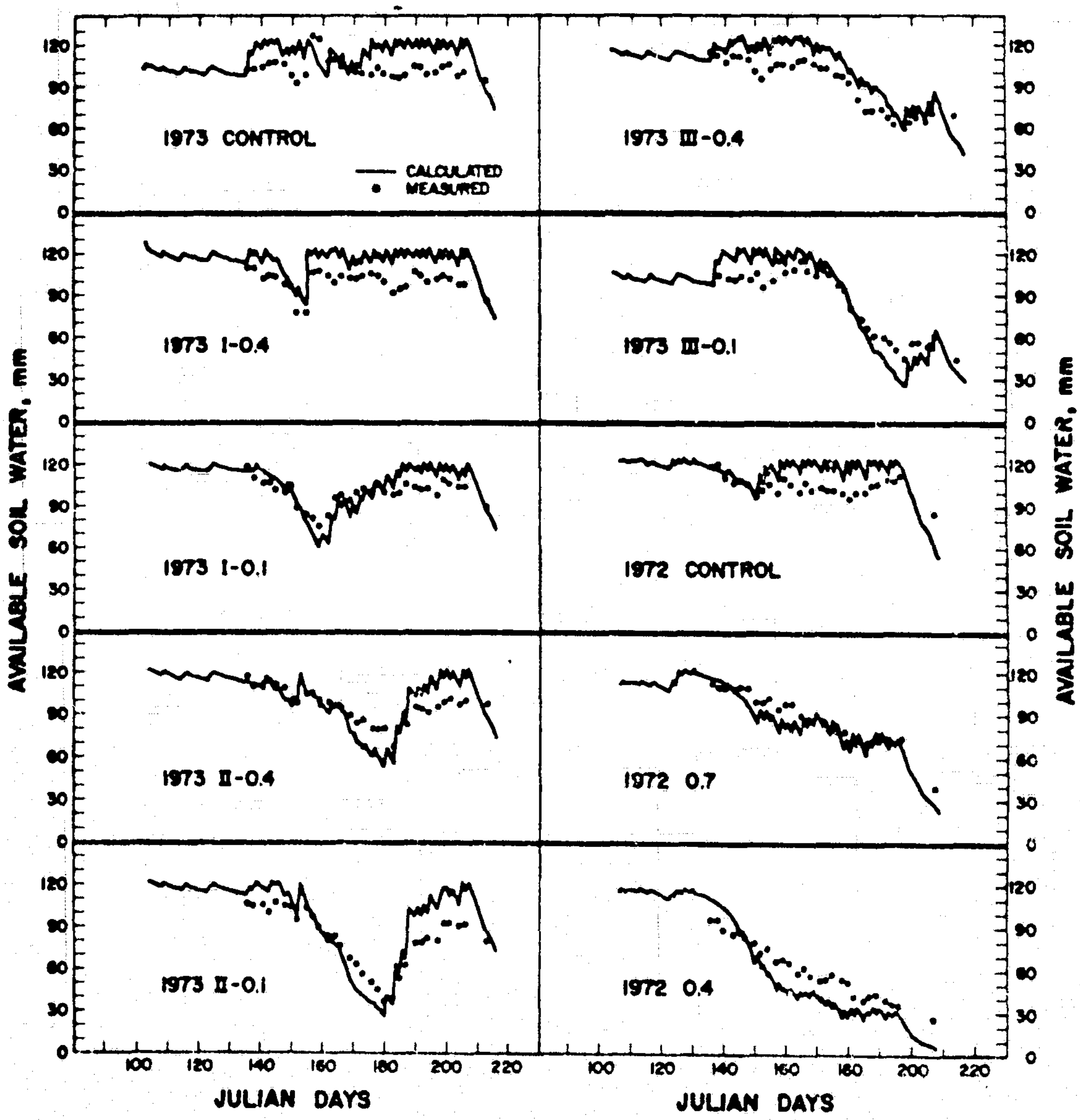
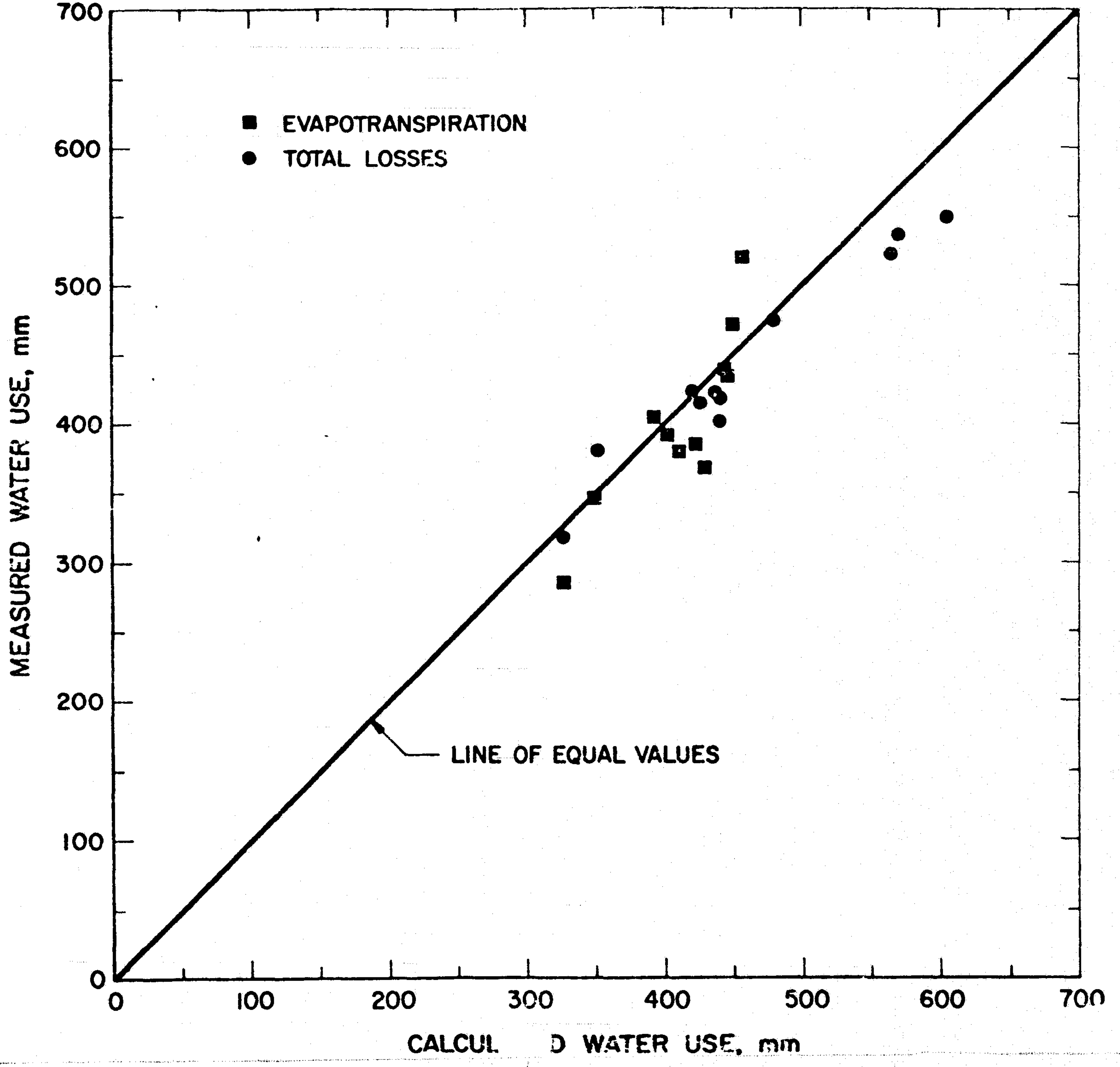


Figure 4. Comparison of measured soil water content with the results of the soil water balance model calculations.



EVAPOTRANSPIRATION
TOTAL LOSSES
LINE OF EQUAL VALUES
MEASURED WATER USE, mm
CALCUL D WATER USE, mm
0
100
200
300
400
500
600
700